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# ***U.S. PATENT APPLICATION***

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***Invention:*** ELECTROMAGNETIC LOAD DRIVE APPARATUS

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## ***SPECIFICATION***

## ELECTROMAGNETIC LOAD DRIVE APPARATUS

### CROSS REFERENCE TO RELATED APPLICATION

This application is based on and incorporates herein by  
5 reference Japanese Patent Application No. 2002-366060 filed on  
December 18, 2002.

### FIELD OF THE INVENTION

This invention relates to an electromagnetic load drive  
10 apparatus.

### BACKGROUND OF THE INVENTION

A variety of actuators are in practical use for producing  
a driving force by flowing an electric current into an inductive  
15 element such as a solenoid and varying the electromagnetic state.  
In an internal combustion engine, for example, such an actuator  
is mounted on an injector that injects fuel, and drives the valve  
of the injector.

A drive apparatus for driving the electromagnetic load  
20 having the inductive element includes a capacitor as a capacitive  
element in addition to a battery which is a DC low voltage power  
source. In this apparatus, the energy accumulated in the  
inductive element due to the supply of electric power is recovered  
by the capacitive element by generating a counter electromotive  
25 force at the time when the operation of the electromagnetic load  
is stopped (EP 0548 915A1, JP 2598595).

In this apparatus, the electric power is supplied to the inductive element from the capacitive element until the voltage across the terminals of the capacitive element becomes equal to the voltage across the terminals of the low voltage power source. Thereafter, the electric power is supplied from the low voltage power source.

The actuator utilizing the inductive element is highly appreciated for its response characteristics when the current supplied to the inductive element rises quickly. The rise of current supplied to the inductive element varies nearly in proportion to the voltage applied to the inductive element.

When it is desired to increase the voltage applied to the inductive element, the capacitance of the capacitive element may be decreased to elevate the voltage across the terminals of the capacitive element after the energy is recovered. From the breakdown voltage of the capacitive element, however, it is not allowed to increase the voltage across the terminals of the capacitive element.

Further, as the power source is shifted to the low voltage power source, there is almost no change in the electric current that flows into the inductive element. Namely, the energy accumulated in the inductive element does not increase so much. All energy that had been held before the operation is not recovered by the capacitive element. Therefore, the loss of energy must be replenished until the next operation. However, the energy cannot be sufficiently replenished when the interval

is short until the next operation of the actuator. For example, when the same injector is consecutively operated within short periods of time like the multi-step injection of the internal combustion engine, the response drops toward the subsequent operations.

#### SUMMARY OF THE INVENTION

It is an object of the present invention to provide an electromagnetic load drive apparatus that attains a quick response to a sufficient degree.

According to this invention, when an inductive element operates, the applied voltage becomes the sum of a voltage across the terminals of a low voltage power source and a voltage across the terminals of a capacitive element. Therefore, the rise of current flowing into the inductive element becomes sharp by the voltage across the terminals of the low voltage power source.

Further, the inductive element accumulates the energy of an amount greater, by the voltage across the terminals of the low voltage power source, than that of the energy held by the capacitive element at the start of operation of the inductive element, and avoids a large decrease in the amount of energy recovered by the capacitive element as compared to the value at the start of operation of the electromagnetic load. Therefore, the response does not drop even when the interval is short until the next operation of the electromagnetic load. When the operation of the inductive element is discontinued, the potential

of the capacitive element is brought close to the reference voltage as compared to that of during the operation, and energy can be easily recovered from the inductive element.

Preferably, even when the capacitive element of a small capacity is employed to elevate the voltage across the terminals, the electric current can be supplied to a sufficient degree by using an assisting capacitive element even after the voltage across the terminals of the capacitive element has sharply dropped. As a result, energy is accumulated to a sufficient degree in the inductive element, and the voltage across the terminals of the capacitive element after having recovered the energy can be easily recovered up to a voltage at the start of the electromagnetic load operation.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects, features and advantages of the present invention will become more apparent from the following detailed description made with reference to the accompanying drawings. In the drawings:

Fig. 1 is a circuit diagram of an electromagnetic load drive apparatus according to a first embodiment of the invention;

Fig. 2 is a timing chart illustrating the operation of the first embodiment;

Fig. 3 is a circuit diagram of an electromagnetic load drive apparatus according to a second embodiment of the invention;

Fig. 4 is a graph illustrating the operation of the second

embodiment;

Fig. 5 is a circuit diagram of an electromagnetic load drive apparatus according to a third embodiment of the invention;

Fig. 6 is a graph illustrating the operation of the third  
5 embodiment;

Fig. 7 is a graph comparing the electromagnetic load drive apparatuses of the first to the third embodiments;

Fig. 8 is a circuit diagram of an electromagnetic load drive apparatus according to a fourth embodiment of the invention;

Fig. 9 is a first timing chart illustrating the operation  
10 of the fourth embodiment;

Fig. 10 is a second timing chart illustrating the operation of the fourth embodiment; and

Fig. 11 is a graph comparing the electromagnetic load drive  
15 apparatuses of the first and the fourth embodiments.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

##### (First Embodiment)

Referring first to Fig. 1 illustrating an electromagnetic  
20 load drive apparatus, an electromagnetic load drive apparatus M is common to a plurality of electromagnetic loads  $A_i$ , and selectively drives the electromagnetic loads  $A_i$ . Its example can be represented by a fuel injector of a MPI system used for internal combustion engines. Namely, in the internal combustion  
25 engine, an injector which is an electromagnetic load for injecting fuel is provided for each of the cylinders, and a

solenoid which is an inductive element included in the injector changes the valve inserted in the nozzle of the injector between a seated state and a lifted state upon changing over the electromagnetic attractive force to thereby change over the fuel injection and fuel interruption. In the first embodiment, three electromagnetic loads  $A_i$  are provided for a three-cylinder internal combustion engine.

The electromagnetic loads  $A_i$  have solenoids  $L_i$  corresponding to each of the electromagnetic loads  $A_i$  in a 1-to-1 manner. Each solenoid  $L_i$  is provided with feeder lines  $W_b$  and  $W_c$ . The feeder line  $W_b$  becomes a single line at a base end, and the electric power is supplied from a battery  $B$  which is a common low voltage power source via a diode  $D_b$  provided for the feeder line  $W_b$ . The diode  $D_b$  is connected to a terminal  $BT_1$  (positive side terminal  $BT_1$  of the battery  $B$ ) on the positive side of the battery  $B$  which is a terminal of the side opposite to a terminal  $BT_2$  of the reference potential side. The terminal  $BT_2$  (negative side terminal  $BT_2$  of the battery  $B$ ) on the negative side of the battery  $B$  which is a terminal of the reference potential side to serve as the reference potential portion. The diode  $D_b$  has the anode that is connected to the positive side terminal  $BT_1$  of the battery  $B$ . The direction in which the current is supplied from the battery  $B$  to the solenoid  $L_i$  is the forward direction. Therefore, the current is inhibited from flowing in a direction reverse to the supply of current to protect the battery  $B$ .

The feeder line  $W_c$  is provided for a capacitor  $C$  which is

a capacitive element serving as a source for feeding electric power to the solenoid Li. The capacitor C has one terminal CT1 that is connected to the diode Db through a switch SWr and a diode Dc. The diode Dc has the anode that is connected to one terminal CT1 of the capacitor C through the switch SWr. The direction in which the current is supplied from the capacitor C to the solenoid Li is the forward direction. A resonance circuit is formed by the capacitor C and the solenoid Li. The current tends to flow in a direction opposite to the direction in which the current is supplied. However, the current is inhibited from flowing in the direction opposite to the direction in which the current is supplied, and the current is prevented from flowing into the solenoid Li in the direction opposite to the normal flow of current. This prevents the occurrence of electromagnetic action in the solenoid Li in the direction opposite to the normal direction.

A switch SWi, which operates as switching means and selection means, is provided between the terminal BT2 (negative side of the battery B) and a terminal LT2 (terminal of the negative side) on the side opposite to the terminal (terminal of the positive side) LT1 of the solenoid Li that is connected to the positive side terminal BT1 of the battery B through the diode Db, thereby to change over the supply and interruption of current from the battery B and the capacitor C. This selects the electromagnetic load Ai that is to be operated and specifies the operation period thereof, i.e., selects the cylinder into which



the fuel is to be injected and specifies the injection period in the case of an internal combustion engine. As will be described later, further, the switch SWi is used for controlling the voltage Vc across the terminals of the capacitor C.

5           The other terminal CT2 on the reference potential side of the capacitor C is grounded through a switch SWc which is switching means, and assumes a reference potential when the switch SWc is turned on. One terminal CT1 is referred to as the positive side terminal and the other terminal CT2 is referred to as the negative side terminal. The terminal CT2 is further  
10           connected to the positive side terminal BT1 of the battery B through a switch SWb which is switching means. Upon changing over the switches SWb and SWc, the connection between the battery B and the capacitor C can be changed over. That is, when the  
15           switch SWb is turned on and the switch SWc is turned off, the positive side terminal BT1 of the battery B is rendered conductive to the negative side terminal CT2 of the capacitor C, whereby the voltage applied to the solenoid Li becomes equal to the sum of the voltage Vb (voltage across the battery terminals) across the  
20           terminals of the battery B and the voltage Vc (voltage across the capacitor terminals) across the terminals of the capacitor C provided the switches SWi and SWr are turned on (first state).

          When the switch SWb is turned off and the switch SWc is turned on, on the other hand, the negative side terminal CT2 of  
25           the capacitor C is connected to the negative side terminal BT2 of the battery B (second state). As will be described later, the

energy can be recovered by the capacitor C from the solenoid Li provided the switch SWi is turned on.

A recovering line Wi is provided between the negative side terminal LT2 of the solenoid Li and the positive side terminal CT1 of the capacitor C being corresponded to the solenoid Li in a 1-to-1 manner to recover in the capacitor C the energy accumulated in the solenoid Li. A diode Di is provided in the recovering line Wi in such a manner that the direction in which the current is recovered by the capacitor C from the solenoid Li is the forward direction, i.e., in such a manner that the anode is connected to the solenoid Li.

The diode Di inhibits the flow of current in a direction opposite to the flow of recovery current. Therefore, no current is recovered by the capacitor C1 from the solenoid Li. When all the energy in the solenoid Li migrates into the capacitor C1, the recovery of energy is completed without involving the switching operation. Further, the positive side terminal CT1 of the capacitor C is prevented from being grounded when the switch SWi is turned on like the electromagnetic load Ai in operation.

The switches SWi, SWb, SWc and SWr are constituted by power MOSFETs, and are controlled by a central control unit X. The central control unit X is constructed with a microcomputer or the like, sends control signals Si, Sb, Sc and Sr to the switches SWi, SWb, SWc and SWr to turn the switches SWi, SWb, SWc and SWr on and off. Further, the central control unit X receives a potential (capacitor potential) from the positive side terminal

CT1 of the capacitor C and a potential (voltage  $V_b$  across the terminals of the battery B) from the positive side terminal BT1 of the battery B, and calculates the timings for producing the control signals  $S_i$ ,  $S_b$ ,  $S_c$  and  $S_r$  based on the inputs.

5           The operation of the electro magnetic load drive apparatus M will now be described. Fig. 2 illustrates the state of operation of each of the portions of the electromagnetic load drive apparatus M, assuming that the switch SWc is turned off at timing T0 prior to starting the operation of the electromagnetic load Ai and, then, the switches SWb and SWr are turned on at timing 10 T1. This is the first state where the capacitor potential  $V_i$  rises from the voltage  $V_c$  across the terminals of the capacitor C up to the sum ( $V_c + V_b$ ) of the voltage  $V_b$  across the terminals of the battery B and the voltage  $V_c$  across the terminals of the 15 capacitor C. Further, since the switch SWr is turned on, the positive side terminal CT1 of the capacitor C is conductive to a point where the diodes Db and Dc are connected together. Here, the diode Dc is forwardly biased but the diode Db is reversely biased.

20           Next, at the start (timing T2) of operation of the electromagnetic load Ai in response to the signal  $S_i$ , the switch SWi is turned on that corresponds to any one of the three electromagnetic loads Ai that is to be operated. Then, the voltage ( $V_c + V_b$ ) is applied to the solenoid Li, and a current 25  $I_i$  starts flowing into the solenoid Li. At this moment, the rise of current  $I_i$ , i.e., the rising rate of the current  $I_i$  is

proportional to the voltage ( $V_c + V_b$ ) applied to the solenoid  $L_i$ . The voltage  $V_c$  across the terminals of the capacitor and the capacitor voltage  $V_i$  decrease as the solenoid current  $I_i$  flows.

When the capacitor potential  $V_i$  becomes equal to the voltage  $V_b$  across the terminals of the battery B at timing T3, the diode  $D_b$  is forwardly biased. Then, the voltage applied to the solenoid  $L_i$  assumes the voltage  $V_b$  across the terminals of the battery B. The rising rate of the solenoid current  $I_i$  becomes slower than before.

The operation of the electromagnetic load  $A_i$  is stopped or interrupted as described below. First, the switch  $SW_r$  is turned off prior to stopping the operation of the electromagnetic load  $A_i$  at timing T4. As will be described later, this is to inhibit the current from flowing again into the solenoid  $L_i$  from the capacitor C through the diode  $D_c$ , since the capacitor voltage  $V_c$  rises as the energy is recovered by the capacitor C from the solenoid  $L_i$ .

At timing T4, the switches  $SW_i$  and  $SW_b$  are turned off, and the switch  $SW_c$  is turned on. This is the second state. The switch  $S_i$  is then turned on and off. During the OFF period (T4 to T5) of the switch  $S_i$ , a counter-electromotive force is produced in the solenoid  $L_i$ , the diode  $D_i$  is forwardly biased, and a recovery current flows through a path of solenoid  $L_i$  - diode  $D_i$  - capacitor C, and the energy accumulated in the solenoid  $L_i$  is recovered by the capacitor C. Therefore, the voltage  $V_c$  across the terminals of the capacitor C rises and the capacitor potential

Vi is restored toward the capacitor potential Vc of before starting the operation.

During the ON period (T5 to T6) of the switch Si, a current flows again through the path of battery B - diode Db - solenoid Li - switch SWi - battery B, and the energy accumulates in the solenoid Li. During the next OFF period (T6 to T7), a recovery current flows through the path of solenoid Li - diode Di - capacitor C, and the energy accumulated in the solenoid Li is recovered by the capacitor C.

The central control unit X fixes the switch SWi to OFF as the capacitor potential Vi or the voltage Vc across the terminals of the capacitor assumes a preset end voltage (T7). Thus, the selected electromagnetic loads Ai are successively controlled.

In the illustrated embodiment, the ON period and the OFF period are set to be of the same length. The embodiment, however, is in no way limited thereto only. The ON period may be set to be, for example, of a predetermined length, and the current flowing into the solenoid Li may be monitored such that the OFF period may be terminated, i.e., the ON period may be entered every time when the monitored current becomes 0. The first OFF period (T4 to T5) of the switch Si is long enough for the solenoid current Ii to decrease down to a value at which the electromagnetic load Ai ceases to operate, as a matter of course.

In the electromagnetic load drive apparatus M, at the start of operation of the electromagnetic load Ai, the voltage applied to the solenoid Li becomes the sum (Vc + Vb) of the voltage Vc

across the terminals of the capacitor C and the voltage  $V_b$  across the terminals of the battery B. Therefore the current flowing into the solenoid  $L_i$  rises correspondingly, and the response of the electromagnetic load  $A_i$  is improved.

5           At the start of operation of the electromagnetic load  $A_i$ , further, the solenoid  $L_i$  accumulates the energy larger, by an amount corresponding to the voltage  $V_b$  across the terminals of the battery B, than the energy held by the capacitor C. The energy recovered to the capacitor C is avoided from being greatly  
10       decreased as compared to that of at the start of the operation of the electromagnetic load  $A_i$ . Therefore, the capacitor potential  $V_i$  is recovered up to the voltage at the start of operation through a small number of times of on/off operation of the switch  $S_i$ . Therefore, the response does not drop despite the  
15       interval is short until the next operation of the electromagnetic load  $A_i$ . When the operation of the solenoid  $L_i$  is interrupted, the potential of the capacitor C is brought close to the reference potential by the voltage  $V_b$  across terminals of the battery as compared to that of during the operation, and the energy can be  
20       easily recovered from the solenoid  $L_i$ .

(Second Embodiment)

As shown in Fig. 3, an electromagnetic load drive apparatus M according to a second embodiment is constructed in the similar manner as the first embodiment. In the first embodiment, the  
25       recovery of energy when the operation is stopped is completed as the voltage  $V_c$  across the terminals of the capacitor C assumes

the predetermined end voltage. According to the second embodiment, however, the operation characteristics of the electromagnetic load  $A_i$  can be further improved.

The central control unit X receives the capacitor potential  $V_i$  as well as the positive side potential (= voltage  $V_b$  across the terminals of the battery) of the battery B, and sets a period for completing the charging of the capacitor C based on the capacitor potential  $V_i$  and the voltage  $V_b$  across the terminals of the battery B.

That is, the central control unit X sets the end voltage of the capacitor potential  $V_i$  (= voltage  $V_c$  across the terminals of the capacitor) so that the end voltage does not become constant but that the sum ( $V_b + V_c$ ) of the voltage  $V_b$  across the terminals of the battery and the voltage  $V_c$  across the terminals of the capacitor C becomes constant ( $V_k$ ). Namely, the end voltage is given by ( $V_k - V_b$ ).

Therefore, as the voltage  $V_b$  across the terminals of the battery B varies depending upon the conditions of other loads supported by the battery B, the end voltage varies correspondingly. If the voltage  $V_b$  across the terminals of the battery B drops from  $V_{b2}$  to  $V_{b1}$  as shown in Fig. 4, the end voltage rises from  $V_{c2}$  ( $= V_k - V_{b2}$ ) to  $V_{c1}$  ( $= V_k - V_{b1} > V_{c2}$ ).

Therefore, even when the voltage  $V_b$  across the terminals of the battery B varies, the voltage applied to the solenoid  $I_i$  can be set to be constant at the start of operation. The rise of the solenoid current  $I_i$  can be set to be constant at the start

of operation.

(Third Embodiment)

As shown in Fig. 5, an electromagnetic load drive apparatus M according to a third embodiment is constructed in the similar manner as the second embodiment.

In the third embodiment, the central control unit X sets the timing for completing the charging of the capacitor C based on the capacitor potential  $V_i$  and the voltage  $V_b$  across the terminals of the battery B.

That is, the central control unit X sets the end voltage of the capacitor potential  $V_i$  (= voltage  $V_c$  across the terminals of the capacitor C) so that the sum ( $V_b + V_c$ ) of the voltage  $V_b$  across the terminals of the battery B and the voltage  $V_c$  across the terminals of the capacitor C assumes a predetermined value  $V_s$ .

That is, the central control unit X sets the end voltage of the capacitor potential  $V_i$  (= voltage  $V_c$  across the terminals of the capacitor C) so that the sum ( $V_b + V_c$ ) of the voltage  $V_b$  across the terminals of the battery B and the voltage  $V_c$  across the terminals of the capacitor C assumes the predetermined value  $V_s$ . Here, however, the predetermined value  $V_s$  varies depending upon the voltage  $V_b$  across the terminals of the battery B. Namely, the predetermined value  $V_s$  increases with a decrease in the voltage  $V_b$  across the terminals of the battery B.

As shown in Fig. 6, therefore, as the voltage  $V_b$  across the terminals of the battery B drops from  $V_{b2}$  down to  $V_{b1}$ , the



predetermined value  $V_s$  rises from  $V_{s2}$  to  $V_{s1}$ , and the end voltage rises from  $V_{c2}$  ( $= V_{s2} - V_{b2}$ ) to  $V_{c1}$  ( $= V_{s1} - V_{b1} > V_{c2}$ ). Since  $V_{s2} < V_{s1}$ , in this embodiment, the end voltage of the capacitor potential  $V_i$  ( $=$  voltage  $V_c$  across the terminals of the capacitor C) increases to be greater than that of the second embodiment when the voltage  $V_b$  across the terminals of the battery B drops.

Fig. 7 illustrates the results of measuring the valve response time  $T_r$  of the injector while varying the voltage  $V_b$  across the terminals of the battery B when the electromagnetic load drive apparatuses of the first to the third embodiments (#1 to #3) are applied to the fuel injection device of an internal combustion engine. The valve response is defined by the time from the start of feeding the current to the solenoid  $L_i$  for fuel injection operation until the valve is fully lifted. When the voltage  $V_c$  across the terminals of the capacitor C is simply charged up to the predetermined end voltage like in the first embodiment, the fluctuation in the voltage  $V_b$  across the terminals of the battery B is directly reflected on the rise of the solenoid current  $I_i$  at the start of operation of the electromagnetic load, and the response of valve correspondingly varies.

According to the second embodiment, however, the rising rates of the solenoid currents  $I_i$  at the start of the operation of the electromagnetic load are uniformed, and variation in the valve response is improved. According to the third embodiment, further, the variation in the valve response is more improved than

that of the second embodiment.

This is due to that among the voltages applied to the solenoid Li, the voltage component (Vb) due to the battery B assumes nearly a constant value after the start of operation of the electromagnetic load while the voltage component (Vc) due to the capacitor C tends to decrease as the electric current is fed to the solenoid Li. That is, in the second and third embodiments, as the voltage Vb across the terminals of the battery decreases, the amount of decrease is replaced by the voltage component due to the capacitor C1 that tends to decrease as the current is fed to the solenoid Li. In the second embodiment, therefore, even if the rising characteristics are uniformed right after the start of operation of the electromagnetic loads, the rising characteristics within a predetermined period of time (from T2 to T3 in Fig. 2) at the start of operation of the electromagnetic loads differ depending upon a ratio of the voltage component (Vb) due to the battery B to the voltage component (Vc) due to the capacitor C. Specifically, as the voltage Vb across the terminals of the battery B drops and the ratio of the voltage component (Vc) due to the capacitor C increases, the rising characteristics become slow remarkably in the latter half in the predetermined period of time at the start of operation of the electromagnetic load.

In the third embodiment, when the voltage Vb across the terminals of the battery B decreases, the capacitor potential Vi is made greater than that ( $Vb + Vc = V_k$  (constant)) of the second

embodiment. Therefore, the rising characteristics become slow in the latter half in the predetermined period of time at the start of operation of the electromagnetic load, and variation in the response of valve can be suppressed.

5           The injectors can be contrived in a variety of structures such as the one in which a valve for opening and closing the injection port is directly driven by a solenoid, and the one in which a valve for control is actuated by a solenoid. In any structure, the period in which a current flowing into the solenoid  
10 reaches a sufficient magnitude, affects the response time significantly until a driving force attains the pressure for opening the valve driven by the solenoid or significantly affects the time until the valve is fully lifted. Therefore, the third embodiment of the invention can be applied particularly  
15 preferably to the fuel injection apparatus.

(Fourth Embodiment)

As shown in Fig. 8, an electromagnetic load drive apparatus M according to a fourth embodiment is constructed in the similar manner as the first embodiment.

20           The electromagnetic load drive apparatus M is provided with two capacitors C1 and C2. The capacitor C1 is a capacitive element serving as a power source. The capacitor C2 is an assisting capacitive element. The capacitor C1 is substantially the same as the capacitor C of the first embodiment. The capacitor C2 has  
25 a capacitance larger than that of the capacitor C1. The capacitor C1 is referred to as small capacitor C1, and the capacitor C2 is

referred to as large capacitor C2. The electric power can be fed to the solenoid Li from the small capacitor C1 through a feeder line Wc1, and the electric power can be fed to the solenoid Li from the large capacitor C2 through a feeder line Wc2. The small capacitor C1 and the large capacitor C2 are capable of feeding electric power to the solenoid Li in parallel.

The feeder lines Wc1 and Wc2 are coupled into one through the switch SWr, and are provided with diodes Dc1 and Dc2. The diode Dc1 has its anode connected to the positive side terminal C1T1 of the capacitor C1. The direction in which the current is supplied from the capacitor C1 to the solenoid Li is the forward direction. The diode Dc2 has its anode connected to the positive side terminal C2T1 of the capacitor C2. The direction in which the current is supplied from the capacitor C2 to the solenoid Li is the forward direction.

The diode Dc1 on the side of the small capacitor C1 works substantially in the same manner as the diode Dc in the first embodiment. The diode Dc2 is inserted from the standpoint that a resonance circuit is formed by the large capacitor C2 and the solenoid Li, and that a current tends to flow in a direction opposite to the feed current. The diode Dc2 works to inhibit the current from flowing in a direction opposite to the feed current and prevents the current from flowing into the solenoid Li in a direction opposite to that of normal current.

Further, a terminal of the large capacitor C2 on the side of the diode Dc2 is connected to the positive side terminal BT1

of the battery through a charging line Wa, and the large capacitor C2 can be electrically charged from the battery B. The charging line Wa is provided with a diode Da with its anode on the side of the battery B, and a direction in which the charging current flows from the battery B to the large capacitor C2 is the forward direction.

Next, described below is the operation of the electromagnetic load drive apparatus M. The central control unit X in the electromagnetic load drive apparatus M executes substantially the same control operation as that of the first embodiment. Fig. 9 illustrates the state of operation of each of the portions of the electromagnetic load drive apparatus M. The control operations of the switches SWc, SWb, SWr and SWi for starting the operation of the electromagnetic load Ai are the same as those of the first embodiment. In a state where the switch SWc is ON and the switch SWb is OFF, the diode Da is forwardly biased, and the large capacitor C2 is charged up to the voltage Vb across the terminals of the battery B.

As the switch SWb is turned on at timing T1, therefore, the potential (large capacitor potential) Vi2 of the large capacitor C2 on the side of the diode Dc2 is raised by the voltage Vb across the terminals of the battery B like the potential (small capacitor potential) Vi1 of the small capacitor C1 on the side of the diode Dc1. Further, the small capacitor C1 is charged up to a voltage higher than the voltage (=Vb) across the terminals of the large capacitor C2 as the energy is recovered from the solenoid Li as

will be described later. Therefore, the large capacitor potential  $V_{i2}$  is lower than the small capacitor potential  $V_{i1}$ , and the diode  $Dc2$  is reversely biased.

In feeding the electric power to the solenoid  $Li$  after timing  $T2$ , the diode  $D6$  is reversely biased as described above, and the electric power is fed to the solenoid  $Li$  from the small capacitor  $C1$ .

Then, as the small capacitor potential  $V_{i1}$  drops down to the large capacitor potential  $V_{i2}$  ( $= 2V_b$ ), the electric power is, then, supplied from both the small capacitor  $C1$  and the large capacitor  $C2$ . Then, as is understood from Fig. 9, the small capacitor potential  $V_{i1}$  ( $=$  large capacitor potential  $V_{i2}$ ) which is the voltage applied to the solenoid  $Li$  drops more slowly than the small capacitor potential  $V_{i1}$  which is the voltage applied to the solenoid  $Li$  used. Therefore, the solenoid current  $I_i$  increases without being greatly suppressed from rising.

The operation of the electromagnetic load  $A_i$  is discontinued by turning the switches  $SW_i$  and  $SW_b$  off and the switch  $SW_c$  on at timing  $T4$  as in the first embodiment. In the fourth embodiment, however, the electric power is supplied from both the small capacitor  $C1$  and the large capacitor  $C2$  as described above. Therefore, the voltage  $V_{c1}$  across the terminals of the small capacitor can be recovered at one time up to the voltage before starting the operation in recovering the energy only to the small capacitor  $C1$ . Therefore, the central control unit  $X$  does not charge the small capacitor  $C1$  by turning

the switch  $S_i$  on and off. However, the central control unit X may charge the small capacitor C1 to cope with the loss of energy due to the passage of time, as a matter of course.

Thus, the next operation can be conducted without separately charging the small capacitor C1 as opposed to the first embodiment (period from T5 to T7). Accordingly, the embodiment can be desirably adapted even when the interval is very short until the next operation of the electromagnetic load  $A_i$ . There is required neither a DC-DC converter for obtaining a necessary application voltage nor a large capacitor that is electrically charged with the voltage thereof, and the cost can be decreased.

Upon changing over the switches  $SW_i$ ,  $SW_b$  and  $SW_c$  at the time of discontinuing the operation of the electromagnetic load  $A_i$ , the diode  $D_a$  is forwardly biased and the large capacitor C2 is electrically charged from the battery B through the diode  $D_a$ , as a matter of course.

Fig. 10 illustrates an example where the interval is short until the operation of the next electromagnetic load  $A_i$ , and represents a multi-step injection in injecting fuel in, for example, an internal combustion engine. The voltage  $V_{c1}$  across the terminals of the small capacitor C1 can be recovered at one time up to the voltage  $V_c$  of before starting the operation. Hence, a plurality of electromagnetic loads can be operated successively. Further, the plurality of electromagnetic loads can be successively operated at a short interval. In this case, the drive circuit need not be provided for each of the electromagnetic

loads, and the cost can be decreased.

The voltage  $V_{c1}$  across the terminals of the small capacitor restored by recovering the energy accumulated in the solenoid  $L_i$ , varies depending upon the capacity of the large capacitor  $C_2$  and may, hence, be set by taking into consideration the rising characteristics of the required solenoid current  $I_i$ , such as the solenoid current  $I_i$  at  $T_3$ .

Fig. 11 compares the valve response  $T_r$  of the first embodiment (#1) without the large capacitor  $C_2$  with the valve response  $T_r$  of the fourth embodiment (#4). It will be understood that the fourth embodiment exhibits superior valve response irrespective of the voltage  $V_b$  across the terminals of the battery B.

The fourth embodiment having the large capacitor  $C_2$  employs the small capacitor  $C_1$  having a sufficiently small capacity to improve the rising characteristics of the solenoid current  $I_i$ . Therefore, if the capacitances of the capacitors  $C_1$  and  $C_2$  are denoted by  $C_1$  and  $C_2$ , then, it is preferred that  $C_1 < C_2$  as in this embodiment. The capacitor  $C_2$  is to supplement the lack of the power-feeding ability of the capacitor  $C_1$  that recovers the energy from the solenoid  $L_i$ . Depending upon the amount of supplementing the required power-feeding ability, however, the capacitor  $C_2$  may have a capacitance smaller than that of the capacitor  $C_1$ .

The present invention may be modified in various ways without departing from the spirit of the invention.